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Objectives and Planning of Forest Inventories

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Introduction

Forest inventories, also called forest resources assessments, can be understood as "the procedure for obtaining information on the quantity and condition of the forest resource, associated vegetation and components and many of the characteristics of the land area on which the forest is located" (Hush et al. 2003). The term "forest inventory" refers to both, a catalog of information on forests and the measurement and assessment of data on which the information is based. Forest inventory forms the foundation of forest planning and forest policy. While early designs of sustainable forest management and forest inventory focused on timber production (Hartig 1819; Cotta 1804), modern forest inventory designs support a holistic view of forest ecosystems addressing not only timber production but the multiple functions of forests as well as the need to understand the functioning mechanisms of forest ecosystems (Lund 1998; Corona et al. 2003; Köhl et al. 2006; Corona and Marchetti 2007).

Forests have to be managed judiciously not only for environmental protection and other services but also for various products and industrial raw material. In some parts of the world, biological resources are being depleted faster than they can regenerate mainly caused by unsustainable management and illegal logging. Following the 1992 UNCED conference in Rio de Janeiro, considerable progress has been made in the area of sustainable forest management. Among others, the International Tropical Timber Organization (ITTO) and the Forest Stewardship Council (FSC) developed criteria and indicators for sustainable forest management and certification. The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) described measures to mitigate greenhouse gasses and addressed in particular the impact of deforestation and afforestation on global climate change. The Convention on Biological Diversity (CBD) that was ratified in 1994 deals with the protection and maintenance of biodiversity (CBD 1995). Forest inventories facilitate a multifaceted analysis and study of forests not only as important source of subsistence, employment, revenue earnings, and raw materials to a number of industries but also for their vital role in ecological balance, environmental stability, biodiversity conservation, food security, and sustainable development of countries and entire biosphere (Corona and Marchetti 2007).

Despite the fact that forest inventories are carried out for different purposes and in different environments, there are several general implications to be considered for any assessment:

1. The information provided has to satisfy user needs. Therefore, the inventory objectives need to be defined by the joined efforts of inventory specialists and the parties involved (e.g., forest authorities, forest owners, wood-processing industries, land-use planning and environmental protection agencies, consumers of secondary forest products, wildlife organizations, or local societies).

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2. The information has to be objective. Objective information requires the objective assessment of data and a clear reference to the population sampled. Any interpretation or evaluation of the content of information provided should be omitted.
3. Transparency: the assumptions and methodologies utilized need to be clearly explained and documented.
4. The methodologies as well as the terms and definitions applied need to be consistent over time. Otherwise one cannot distinguish between true change and change due to changes in methodologies or terms and definitions. Changes should be only applied when it can be argued that the benefits outweigh the problems introduced.
5. The information has to be reliable. Any forest inventory is subject to a certain degree of uncertainty, introduced by sampling, measurements, and models applied. It is good practice to specify the degree of uncertainty of any figure provided. As sample-based results are always subject to sampling errors, it is necessary to accompany any statistical estimate with estimates of sampling error or confidence interval. Measures for quality control and assurance need to be introduced in order to improve reliability.
6. The information must be assessed in a cost-efficient way. For a given budget, the inventory design resulting in the most reliable estimates needs to be selected among different design alternatives. Alternatives can be based on different sampling designs, sampling intensities, or data sources.
7. The results of an inventory should be intuitively clear for potential users. Users are normally not very familiar with sampling statistics, and thus the results should not require a PhD in statistics for any immediate and basic interpretation. Users will have confidence only in information that they can understand.
8. Planning of a forest inventory is a complex task that involves the expertise from many fields. Thus experts from silviculture, forest management planning, economy, policy, ecology, or timber products need to be consulted at an early stage.

Information on forest resources in a defined area can be obtained by either (1) a total tally of all trees or (2) sample surveys that utilize representative samples to draw inference for the area of interest. As total tallies are time consuming, they qualify only for small, forested patches. Therefore, forest resources assessments generally use sample-based techniques. A sample survey consists of standardized approaches to collect information and utilizes four components (Wright and Marsden 2010):

1. *Sampling*: the selection of representative samples from populations, whose observed characteristics provide unbiased information of the characteristics of those populations
2. *Inference*: the generalization of sample statistics to estimate population parameters within calculable error margins
3. *Assessment*: strategies to collect reliable and valid information on individual members of the population
4. *Analysis*: (multivariate) data analysis techniques for the identification of complex statistical relationships among many characteristics of the population

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Objectives of Forest Inventories

Inventory objectives define the specific results that are to be achieved within a time frame and with available resources. They are the basic reference for planning, activities, and the evaluation of performance. Thus the objectives of an inventory have to be laid down in a very early phase of inventory planning. Three specific aspects should be considered when determining inventory objectives (FAO 1998):

1. Objectives need to be determined jointly by the people who will use the results, including forest managers, planners, and decision makers, as well as by inventory specialists. Inventory objectives should not be determined by inventory specialists alone.
2. Not all inventory objectives have the same level of importance. Some have higher priority than others and it is the objectives having highest priority that should determine the inventory design and the presentation of results.
3. Inventory objectives should reflect the physical effort that will be required to conduct an inventory, the organization, estimated costs and time, the existing knowledge of resources, the availability of specific aspects of inventory technologies, and institutional capability. All have a direct bearing upon the implementation of an inventory. An overriding consideration is that an inventory must be practicable and achievable. The value of an incomplete inventory that lacks important information and thus limits the possibilities for inference could be zero or close to zero.

All objectives should be SMART:

Specific	Well defined
	They are clear to anyone that has a basic knowledge of the project
Measurable	They provide quantifiable measures of achievement and variance from set objectives
Agreed upon	Have agreement between the users and the project team on what objectives should be
Realistic	Looking at the resources, knowledge, and time available, can the objective be accomplished?
Time framed	How much time is needed to accomplish the objective?
	Having too much time can affect the project performance

As the thematic scope of forest inventories can vary considerably, it is advisable to review global initiatives and obligations in order to get a broad view on potential information topics to be covered by a forest inventory. The United Nations Conference on Environment and Development, Rio de Janeiro, 1992, produced a nonlegally binding document with recommendations for the conservation and sustainable management of forests (United Nations 1992). This document is known as the "Forest Principles" and may serve as a framework for the definition of inventory objectives.

Box 1: Forest Principles (Excerpt)

Forestry issues and opportunities should be examined in a holistic and balanced manner within the overall context of environment and development, taking into consideration the multiple functions and uses of forests, including traditional uses, and the likely economic and social stress when these uses are constrained or restricted, as well as the potential for development that sustainable forest management can offer.

Source: United Nations (1992)

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ITTO, TARA, CIFOR, ATO, and CCAD as well as the Tarapoto Proposal of Criteria and Indicators for Sustainability of the Amazon Forest, UNEP/FAO Expert Meeting on Criteria and Indicators for Sustainable Forest Management in Dry-Zone Africa, or the Lepaterique Process of Central America expanded on the Forest Principles and developed systems of criteria and indicators for sustainable forest management for managed forests, natural forests, and plantations, which cover administrative, economic, legal, social, technical, and scientific issues. Criteria define the essential factors of forest management against which forest sustainability may be assessed. Each criterion relates to a key management factor, which may be described by one or more qualitative, quantitative, or descriptive indicators. Through measurement and monitoring of selected indicators, the effects of forest management action, or inaction, can be assessed and evaluated and action adjusted to ensure that forest management objectives are more likely to be achieved. Table 1 (after FAO 1998) summarizes the criteria and indicators identified by the processes and initiatives and facilitates the definition of inventory objectives.

As not all objectives have the same importance, the priority of inventory objectives has to be assessed before designing the inventory. Before a final decision on the inventory objectives, all issues that could constrain an implementation of the inventory should be listed and considered. Issues include cost limits, availability of staff, presentation of the findings, the schedule, or the population for which estimates should be given.

The listing of inventory objectives should not be confused with the list of attributes to be assessed or derived. Based on the objectives, the attributes for field assessments, remote sensing imagery, or other data sources have to be derived. Figure 1 gives an example for the indicator “growing stock.” The objective “productive function of forests” is described by several indicators such as “percentage of forests managed according to management plans,” “growing stock,” “wood production,” or “annual balance between growth and removals of wood products.” The indicator “growing stock” is quantified by the attribute “volume over bark,” which is derived by volume functions. Attributes assessed in the field (e.g., diameter at breast height, tree height, upper stem diameters) are used as input variables for regression functions with the volume over bark as dependent variable.

A Typology of Forest Inventories

Forest inventories can be differentiated according to combination and emphasis of different inventory objectives and the size of the area to be surveyed.

Global forest resources assessments are conducted to determine forest resources at the global level. This usually means the compilation of results from individual national inventories. Thanks to advances in remote sensing techniques, satellite data can now be used to determine the distribution of forest vegetation throughout the world (Gerrand et al. 2009; Huete and Saleska 2010; Achard et al. 2010; Stibig et al. 2014). Global forest inventories were conducted by the FAO since 1946 (FAO 2010). The first FAO-led assessments were dominated by studies on timber supply. Today the Forest Resources Assessment (FRA) adopted the design of sustainable forest management as a reporting framework. The economic, ecological, and social elements of forests are covered as well as the legal, policy, and institutional framework.

The FRA does not conduct an own survey. For the FRA 2010, a total of 233 countries and areas contributed data on the base of a harmonized reporting scheme. Results are presented for six regions and 12 subregions and for seven themes (FAO 2010):

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Table 1 Criteria and indicators for sustainable management (After FAO 1998)

Criterion	Indicator
1. Extent of Forest Resources and Global Carbon Cycles	Area of forest cover Wood growing stock Successional stage Age structure Rate of conversion of forest to other use
2. Forest Ecosystem Health and Vitality	
External Influence	Deposition of air pollutants Damage by wind erosion
Forest Vitality Indicators	Incidence of defoliators Reproductive health
Forest Influence Indicators	Insect/disease damage Fire and storm damage Wild animal damage
Anthropogenic Influence Indicators	Competition from introduction of plants Nutrient balance and acidity Trends in crop yields
3. Biological Diversity in Forest Ecosystems	
Ecosystem Indicators	Distribution of forest ecosystems Extent of protected areas Forest fragmentation Area cleared annually of endemic species Area and percentage of forest lands with fundamental ecological changes Forest fire control and prevention measures
Species Indicators	Number of forest-dependent species Number of forest-dependent species at risk Reliance of natural regeneration Resources exploitation systems used Measures in situ conservation of species at risk
Genetic Indicators	Number of forest-dependent species with reduced range
4. Productive Functions of Forests	Percentage of forests/other wooded lands managed according to management plans Growing stock Wood production Production of non-wood forest products Annual balance between growth and removals of wood products Level of diversification of sustainable forest production Degree of utilization of environmentally friendly technologies
5. Protective Functions of Forests	Soil conditions Water conditions Management for soil protection Watershed management Areas managed for scenic and amenity purposes Areas and percentage of forest lands managed for environmental protection Infrastructure density by FMU category

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Table 1 (continued)

Criterion	Indicator
6. Socioeconomic Functions and Conditions	
Indicators for Economic Benefits	Value of wood products
	Value of non-wood products
	Value from primary and secondary industries
	Value from biomass energy
	Economic profitability of SFM
	Efficiency and competitiveness of forest product production, processing, and diversification
	Degree of private and non-private involvement in SFM
	Local community information and reference mechanisms in SFM
Indicators for the Distribution of Benefits	Employment generation/conditions
	Forest-dependent communities
	Impact on the economic use of forests on the availability of forests for local people
	Quality of life of local populations
	Average per capita income in different forest sector activities
	Gender-focused participation rate in SFM
7. Political, Legal, and Institutional Framework	Legal framework that ensures participation by local governments and private landowners
	Technical and regulatory standards of management plans
	Cadastral updating of the FMU
	Percentage of investment on forest management for forest research
	Rate of investment on the FMU level activities: regeneration, protection, etc.
	Technical, human, and financial resources

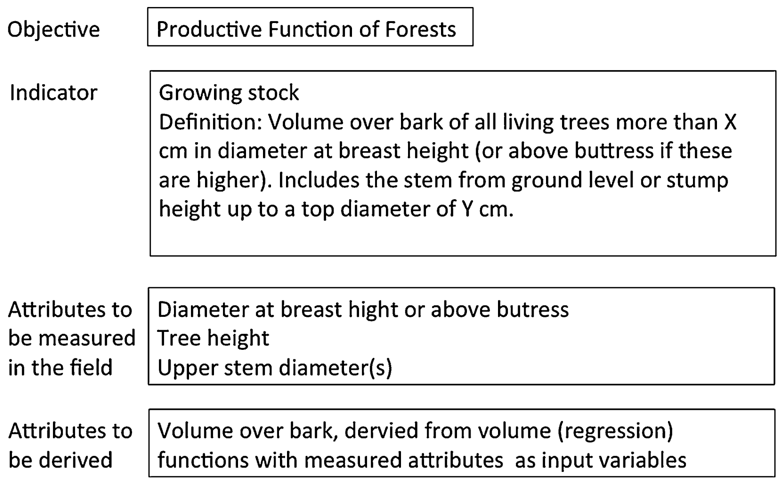

Fig. 1 Objectives, indicators, and attributes

- Extent of forest areas
- Forest biological diversity
- Forest health and vitality
- Protective functions of forest resources
- Productive functions of forest resources
- Socioeconomic functions of forests
- Legal, policy, and institutional framework

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A **national forest inventory** (NFI) is carried out in a specific country and provides information about forest resources. The reporting framework is generally oriented toward sustainable forest management and the multiple ecosystem services and functions of forests. Often the data assessed by NFIs are used to develop timber supply studies that predict future increment and potential harvesting volumes for production forests. The results of NFIs support policy decisions, are utilized by the timber sector (e.g., timber supply, investments) and environmental administrations, and serve as input to scientific studies.

National forest inventories can be realized as sample-based inventories covering the entire country or as a compilation of stand-level data assessed for forest management planning. The latter was common practice in Eastern European countries. The origins of sample-based NFIs date back to the 1920s, when surveys were conducted in the European Nordic countries and in the United States (Ilvessalo 1927; Tomppo et al. 2010). Today NFIs are generally tailor-made sample surveys designed for specific needs and forest characteristics and thus vary from country to country (Tomppo et al. 2010). This holds true for the systems of nomenclature applied as well, which aggravates comparisons of NFI results between countries (Köhl et al. 2000).

Generally, field surveys and remote sensing serve as key data sources. NFIs are designed as inventories at successive occasions, utilizing either periodic assessments or “rolling” surveys that assess a proportion of the country each year (Scott et al. 1999).

Regional forest inventories register only a part of the national forested area and usually cover some hundreds of thousands up to 2 Mio. hectares. Similarly to national inventories, they are intended to provide a general picture of the situation regarding forestry.

Land-cover and land-use inventories record not only forest resources but also the spatial distribution of other types of land cover. There is a distinct difference between land use and land cover:

- *Land cover* is the observed (bio)physical cover of the Earth’s surface. In a strict sense, this concept applies to vegetation and man-made features. For practical applications, land cover includes bare rock and soil as well as water surfaces.
- *Land use* relates to the actions of people in their environment.

Table 2 presents examples for the differences of land use and land cover.

As the major output of land-cover and land-use surveys are maps, the use of aerial photographs and satellite data is of special importance. At the community level, typical methods for assessing land use are walking or windshield (conducted from a car) surveys utilizing GPS tracking systems. Importing land-use data to a GIS system renders further spatial analyses possible (e.g., landscape fragmentation, buffer zone analysis).

An essential step in planning land-cover and land-use inventories is the selection of a land classification system, which is an abstract representation of the real situation on the ground. The class boundaries need to be clearly defined, preferably by objective criteria. A classification system has to be scale and source independent and can be hierarchical (broad-level classes with subclasses) or nonhierarchical. FAO and UNEP created the Global Land Cover Network (GLCN) in order to develop a harmonized approach for the preparation of land-cover data on the local, national, and international level (www.glcn.org).

Reconnaissance inventories aim at furnishing a rough outline of the forest conditions. As well as the location and extent of forested areas, they may aim to register access, species composition, tree dimensions, the distribution of various forest types, and a crude assessment of timber quality (Touber et al. 1989). Through the employment of remote sensing imagery and the restriction of

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field surveys to the minimum, reconnaissance inventories can be conducted at little cost. They frequently serve the preparation of a more intensive forest inventory. Data on the degree of variation and time-and-motion studies conducted during a reconnaissance inventory facilitate the planning of the definitive inventory.

Exploitation surveys or **logging plan surveys** are conducted in forests to provide a basis for the planning of programs for timber harvesting. The main focus is on determining the standing crop, classified according to commercial species, dimensions, timber quality, and assortments and describing the accessibility of the area concerned. Little or no attention is paid to increment, ecological conditions, or sustainability.

Where the economic potential of establishing a wood-processing industry is to be examined, a "**forest industries feasibility study** (FIFS)" is a standard practice. A FIFS comprises the collection of data not only on the forest resources as such but also on the situation regarding demand and marketing, potential sites for processing plants, the job market, sources of water and power, transport possibilities, and existing industries. As the establishment of a timber industry is only worthwhile where there is a steady supply of raw material, it is necessary to determine the forest resources in considerably more detail than is usual in exploitation surveys. In particular, the sustained yield of exploitable timber must be estimated.

Working plan surveys are an intensive type of assessing managed forests. The preparation of working plans for intensively managed but restricted areas requires relatively detailed information. Usually the data are computed on a stand-by-stand basis for each species. Information on increment, detailed forest maps, and data on the quality of the various sites are just as necessary as details on topography, ownership, and access (Schmid 1969; Schmid-Haas et al. 1978).

The various types of inventory are not clearly defined but overlap each other. Neither is their classification fixed, as the increasing demands on the forest will lead to new inventory forms. In addition to the types of inventories described above, special surveys are sometimes conducted, for instance, to determine regeneration, available biomass, or carbon sequestration. Forest inventories may also be classified in terms of time. Static inventories may be conducted simply to determine conditions at a given point in time and do not require consideration of possible subsequent inventories – a fact which considerably simplifies their planning. Nevertheless, the additional expense of permanently marking the sample plots is often a worthwhile investment.

Inventory Planning Phases

The execution of a forest inventory can be divided into four main steps:

1. Definition of the inventory objectives and the information desired
2. Development of the inventory design, including the sampling design, assessment procedures, organization, work flow, and budget
3. Data assessment (field surveys, remote sensing, and gathering of information from other data sources)
4. Analysis of the collected data and publication of the results

Each of these steps requires the knowledge and cooperation of many experts. This includes expertise in inventory statistics, information technology, field assessments, remote sensing, GIS, sustainable forest management, forest ecology, and communication. Due to the need for networking between

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Table 2 Land use versus land cover

Land use	Land cover
Soccer field	Grass
Rangeland	
Golf course	
Recreation area	Forest
	Beach
	Built-up area/shopping mall
Protected area	Forest
	Bare sand
	Tideland

different tasks, it is advisable to base the entire planning on a sound project management design. Good project management deals with three factors: time, cost, and performance. Projects are successful if they are completed on time, within budget, and to performance requirements. In order to bring the many components of a large project into control, there is a large toolkit of techniques, methodologies, and tools. These techniques provide the tools for managing different components involved in a project: planning and scheduling, developing a product, managing financial and capital resources, and monitoring progress (Meredith and Mantel 2012). However, the success of a project will always rest on the abilities of a project manager and the team members. A project life cycle includes the four phases: (1) study phase, (2) design phase, (3) development phase, and (4) operation phase.

The following overview presents individual steps in the four project management phases and is intended to serve as a checklist for inventory planning (Lund 1998; Köhl et al. 2006).

A. Study phase	
User needs assessment	Screening and identifications of potential user groups
	Validate identified user groups by studying information flows between local and upper level as well as among different user groups
	Discuss with individuals their information demands
	Assess information required by laws, mandates, policies, international reporting
	Prepare concise statement of information needs
Initial investigation	Available information on forest resources
	Previous resource assessments in the inventory region
	Organizations with expertise in forest resources assessments, GIS, remote sensing, etc.
	Identify constraints
	Possibilities/needs of outsourcing of specific tasks
Inventory objectives	Necessity of the inventory, information needed
	Potential users of the results
	Formulation of the inventory objectives
	Priorities of the objectives
Determination of the administrative and logistic situation	Bodies responsible for the execution
	Budget (available funds, bodies providing funds, financial administration, time available)
	Legal basis (right of access to privately owned forest, labor laws, protection of private forest owners from information leaks)
	Available information (maps, aerial photographs, data from previous forest inventories and other types of survey, scientific studies in the inventory area, general details on the forest, data on variation, description of the terrain, accessibility, and climatic conditions)

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	Potential use of aerial photography and remote sensing imagery
	Possibilities for recruiting qualified staff
	Available equipment (vehicles, computers and software, measuring instruments, tents)
	Responsible bodies (staff management, financial administration, monitoring of data security, data release, dissemination of data, definition of inventory objectives and methods, execution of field surveys, data evaluation, formulation and release of the final results, publication, additional analyses)
Study phase report	Prepare draft study phase report
	Review of draft by users, administrative bodies, and constituents
	Finalize study phase report
B. Design phase	
General system review	
Compilation of the data catalog and stipulations for measurements	Listing of all variables to be analyzed (depending on inventory objectives)
	Definition of qualitative data
	Instructions for measurement of quantitative data
	Methods of volume determination (e.g., volume functions, points of measurement on the tree, volume inside or outside bark)
Inventory design	Development of sampling design alternatives
	Selection of the optimal (cost-efficient) design
	Description of the design to be employed
	Description of the sampling units, especially their form, size,
	number, and distribution
	Computation of the necessary sample size for each inventory level, survey intensity
	Description of inventory levels (aerial photographic survey, interpretation of satellite data, field surveys, questionnaires)
	Map construction
	Area estimation
	Description of statistical methods for evaluation, estimation procedures, correlations to be applied
	Description of the assessment of road and transport networks
Database design	
Procedures for quality assurance and control	See section “Quality Assurance and Quality Control”
Software selection	
Equipment selection/ acquisition	
Staff recruitment	
Field manual	Fieldwork organization
	Access to plot
	Establishment of permanent plots
	Data collection in the plot
	Data transmission

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Plans for work progress	
Design phase report	
C. Development phase	
Implementation planning	
Computer program design	
User review	
Equipment acquisition and installation	
Field tests/pilot survey	
Computer program testing	
System testing	
Reference manual preparation	
Personnel training	
Changeover plan preparation	
Development phase report preparation	
User acceptance review	
D. Operation phase	
Interpretation of aerial photographs and/or remote sensing data	Instruments (interpretation instruments, computers, software)
	Organizations, staff, competence, duties
	Documentation and backup of the results
Field surveys	Organization, central coordination
	Communication between field survey teams and central coordinators
	Recording and delivery of data
	Training of field staff (localization of sample plot centers, assessments on sample plots, use of instruments)
	Check cruises
Data evaluation	Digitalization of data
	Checking and correction of data
	Data analysis
	Operating, system management, data security
Final report	Preparation (outlet format printed and/or internet) Approval for release
	Reproduction
	Dissemination
Performance evaluation	

Selection of the Optimal Inventory Design

A crucial step in planning a forest inventory is the selection of the optimal inventory design. Given the multitude of inventory objectives, the selection of the most suitable inventory design can be a controversial issue. For example, in a prelogging survey of a concession area, the optimal design for

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the assessment of tree species diversity is markedly different from the optimal design for the assessment of the market value of potential crop trees. According to FAO, forest inventories and assessments aim to "contribute to the sustainable management of forests . . . by providing decision makers and stakeholders with the best possible, most relevant and cost-effective information for their purpose at local, national and international levels" (Saket et al. 2002). Thus, the inventory design is a compromise between the information needed, the reliability of results, and the cost of the survey.

Irrespective of the objective of a survey, alternative inventory concepts exist to choose from, including the utilized data sources (field assessments, remote sensing, maps, etc.) and the design of the sampling units, sampling rules, and sample sizes. The potential design alternatives are influenced by a variety of factors such as the variability of the target population, budget allowance, or availability of auxiliary data sources and information (e.g., maps, remote sensing imagery, volume equations). A rational decision about the optimal design can be made only by comparing the set of alternatives under objective selection criteria that combine information on survey cost and the achievable reliability of the results. This allows for selecting the most cost-efficient design that either provides the best reliability under a given budget or provides the desired reliability by least cost.

A measure of cost-effectiveness is the relative efficiency (Cochran 1977). For fixed cost, relative efficiency of alternative A to alternative B is defined as the ratio of the variances of the two alternatives. Conversely, the cost can be compared for a given precision level. The latter situation is, however, rare in the initial phase of forest surveys. A fixed budget is normally specified. Thus the survey design has to be selected that offers the largest gain in precision for given cost.

The design effect, DEFF, was presented by Kish (Kish 1965) as an alternative concept for comparing sampling designs. Given the same sample size, DEFF is the ratio of the variance of an estimate obtained from a complex sample to the variance obtained from a simple random sample.

Both measures, DEFF and relative efficiency, are used for analytical comparisons of sampling design alternatives. For the practical decisions to be made in the survey planning process, the relation of cost and efficiency, especially the effect of a change of costs on the precision, is needed. In order to meet these requirements, cost-precision relations may be presented in graphical form in order to facilitate the understanding of cost-efficiency relation of different sampling scenarios and of the effect of increased costs on the precision of estimates.

As the information needs of different stakeholders need to be taken seriously, the optimization process should not be targeted to a single attribute. A design tailored for the assessment of commercial timber volume might be insufficient for the assessment of biodiversity. A prioritization of information needs and their underlying attributes is essential.

Cost

Survey costs are made up of fixed and variable cost components. Fixed costs are those that do not vary with sample sizes and design alternatives but are common to all alternatives. Examples for fixed cost are expenses for administration, office rent, or software purchasing. As fixed costs are design independent, they are not to be considered in the optimization process (Scott and Köhl 1993; Groves 2004). Design dependent costs include additional fixed costs for specific design alternatives and variable costs. Costs for visiting and measuring field samples are a typical example for variable costs, which are proportional to the number of field samples assessed. The additional costs of, e.g., stratified sampling would include costs for acquisition, enhancement, and classification of remote sensing data as well as validation of the classification results. The purchase of aerial photographs or digital imagery would be a fixed cost component associated to a design utilizing stratification.

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(Hardcastle and Baird 2008) studied the readiness of 25 tropical countries for monitoring forests and reporting on REDD under the IPCC guidelines. For each country, cost estimates are provided for implementing REDD monitoring and reporting systems, the major divers of costs being forest extent, stratification, and the chosen reliability level, i.e., tier. They present the initial and recurrent cost separately for four alternatives:

1. Tier 2, approach A: an accurate land-cover map is available, 300 sample plots are assessed in situ, all carbon measurements are performed once at the beginning of the program, and future monitoring is focused on the assessment of AD by remote sensing data and requires only minimal field work.
2. Tier 2, approach B: no accurate land-cover map is available, in situ assessments are performed when activity monitoring by remote sensing identifies locations under change, and the in situ sampling intensity is considerably lower than under Tier 2, approach A.
3. Tier 3, ignoring degradation: AD und EF are assessed as under alternative 1 (Tier 2, approach A), but remeasurements are made in permanent in situ sample plots (about 1/3 of the original sample locations).
4. Tier 3, including degradation: alternative 3 is enhanced by further stratification of forests into the two classes: "intact forests" and "non-intact forests," and the number of field plots is moderately increased.

The inventory concepts applied by (Hardcastle and Baird 2008) are generic rather than case specific, as they do not result from a sound inventory design and optimization process on the national level. However, they are used for an approximate comparison of cost required to implement an operation REDD monitoring and reporting scheme on the national level. Figure 2 presents the respective costs for the four alternatives over forest area. The cost per unit area decreases with increasing forest area, as the share of fixed costs in total costs decreases.

Variability

Sample sizes and thus survey costs are directly linked to the variability of the sample population. Variability data for a population can be obtained by prior knowledge or by a pilot survey. For each variance component that is enclosed in the estimation procedures, variability figures have to be specified. For stratified sampling, this means specifying the variance by stratum within the smallest unit of reference for each attribute of interest.

Table 3 presents mean values and possible ranges of aboveground biomass stock per hectare, as given by IPCC (2003) for tropical forests.

Sample Design Alternatives

Different sampling design alternatives can be used in the scope of forest inventories. These sampling designs can employ in situ (field plot) data, remote sensing-based data, or a combination of the two. Combined in situ/Earth observation sample designs use information obtained by remote sensing and field sampling systems simultaneously. The Earth observation data can consist of derived data, such as a classification of remote sensing data into land-cover classes, or reflectance data from optical, radar, or lidar sensors. Variables of interest such as biomass or carbon stock are assessed on a small sample of field plots, and these data are combined with the more densely sampled Earth observation data using statistical estimation procedures in order to generate estimates. Especially where airborne instead of spaceborne sensors are used, it can be prohibitive to cover large areas with remote sensing

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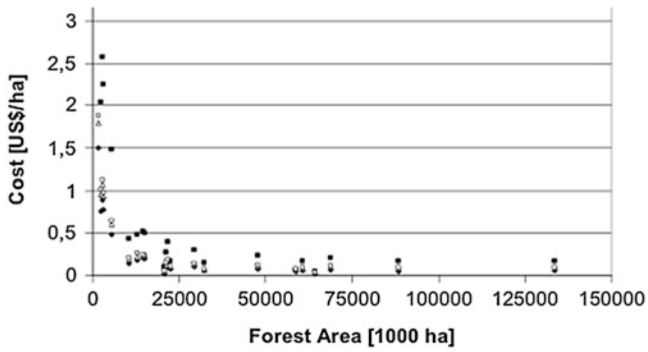

Fig. 2 Cost estimates [US$/ha] in relation to forest area in the scope of REDD (Data from Hardcastle and Baird 2008)

imagery. Similarly, field data collection campaigns can be costly, especially in areas that are hard to access.

Optimization

For each sampling alternative, there exists an optimum combination of sample sizes. These optimum combinations should be used to compare the various design alternatives. In the optimization process, variance functions and cost functions have to be linked in order to derive the optimal (i.e., most cost-efficient) sampling alternative. The optimum sampling design can be defined in two ways:

1. Minimizing cost for a specified level of precision
2. Minimizing variance for a specified cost

In either case, the optimization requires that the cost and precision be expressed in terms of the sampling design and sample sizes. It is good practice to present cost-efficiency graphs for the design alternatives compared, where the achievable percent standard error is plotted over the number of field plots (Fig. 3) or cost (Fig. 4).

The selection of the optimal design by deriving design alternatives is subject to constraints. Therefore a sensitivity analysis needs to be performed where input variables such as cost and variance are inflated. The result will help to identify those designs that are most sensitive for changes in underlying constraints.

Selection Criteria

The selection of the optimal design is not only driven by cost-efficiency. It is good practice to adopt additional selection criteria, such as the tolerance for violations in the selected variance and cost figures, flexibility for future methodological developments, the possibilities to integrate other data sources for sophisticated analyses, the intuitive comprehensibility of the design and the provided results, the complexity of estimation algorithms, the acceptance by the users, or the involvement of local populations. Hence, the selection of the optimal design is a participatory process that involves not only survey statisticians or academia but appropriate and qualified set interest groups.

Defining the Sample Population

It seems to be simple: forest inventories provide information on forests located in the area of interest. What at first glance seems to be simple is in fact a complex issue. There is neither a common

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Table 3 Aboveground biomass stock in m^3 per forest formation (Adapted from IPCC (2003))

	Tropical forests					
	Wet	Moist with short dry season	Moist with long dry season	Dry	Montane moist	Montane dry
Africa	310 (131–513)	260 (159–433)	123 (120–130)	72 (16–195)	191	40
Asia and Oceania: continental	275 (123–683)	182 (10–562)	127 (100–155)	60	222 (81–310)	50
Insular	348 (280–520)	290	160	70	362 (330–505)	50
America	347 (118–860)	217 (212–278)	212 (202–406)	78 (45–90)	234 (48–348)	60

Note: Data are given in mean value and as range of possible values (in parentheses)

definition of forests nor is the area for which the inventory should provide results self-explanatory. For example, one might get information on the forests of a country but omit mangrove forests. Or, does an inventory of logging concessions include natural forest reserves within the concession area? A key question is how to define a forest.

Forest Area Definitions

There exists no unique concept about what qualifies as a forest. The hyperdictionary[1] provides a definition of forest that represents two different aspects:

- The trees and other plants in a large densely wooded area
- Land that is covered with trees and shrubs

When we talk about forest area, we relate to the area covered with trees and shrubs. National legislations often have a legal definition of forest, but they are generally not applicable to forest resources assessments. Forest is a qualitative attribute of an area, which cannot be measured directly. Figure 5 presents three different situations. While the picture on top gives clear evidence of a forest, the picture on the lower left shows a tree outside forests. On the lower right side, an example from the Swiss Alps is given, where trees grow close to the timberline. A predominant characteristic of forests close to natural timberlines is that tree density is gradually lowered toward the timberline. Thus, forest area definitions need to draw the borderline between trees inside a forest and trees outside forests.

Forest area definitions utilize a set of quantifiable and measurable attributes to separate forest from non-forest land. In order to increase the reliability of forest area assessments, forest area definitions are based upon attributes that can easily be measured, such as crown cover, size or width of the forested patch, tree height, or productivity. For those attributes, threshold values are specified, and whenever a patch qualifies for the selected set of attributes, the patch is considered to be forested land. Forest area definitions may also contain specifications about the allowed or disallowed use of forests and forest types.

The set of attributes selected as well as the specified threshold values vary in individual forest area definitions. Table 4 shows some forest area definitions used by international organizations.

Köhl et al. (2000) studied the effect of different national forest area definitions on the estimated size of forest area in a simulation study. Differences in the spatial distribution of trees and forested patches were simulated in computer-generated forest/non-forest maps. The computer-generated

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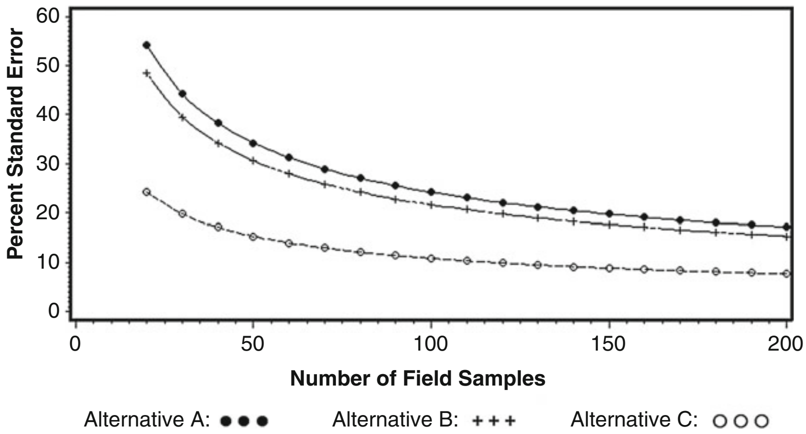

Fig. 3 Sampling design alternatives: percent standard error over number of field samples

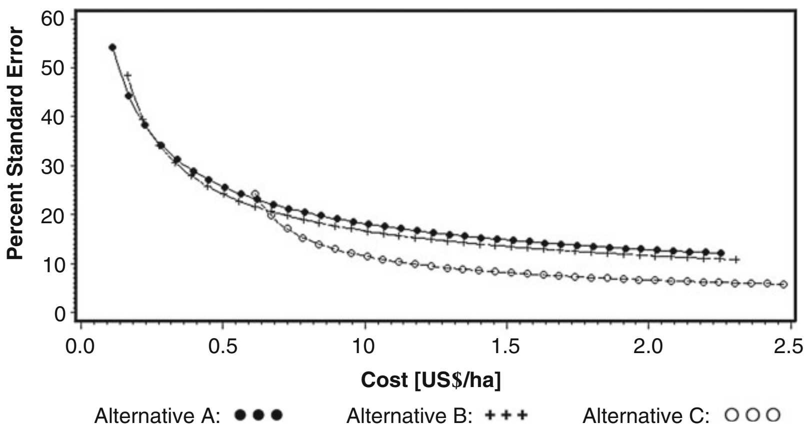

Fig. 4 Sampling design alternatives: percent standard error over cost

forests were used to simulate the impact of exchanging one national definition with another in a number of European countries. This approach allowed to estimate the effect of different national forest area definitions in absolute terms. For example, depending on the chosen definition, the range of the Spanish forest area could vary from about 240,000 km^2 (reference United Kingdom) to 274,000 km^2 (reference Luxembourg).

A universal forest definition remains elusive. Sample-based estimates of forest area must therefore carefully consider the existing forest definition and take competing definitions into account to ensure that estimates of forest areas can be obtained for more than one definition. In the early phase of planning a forest inventory, it should be considered whether only areas currently supporting forest vegetation are to be surveyed or whether former forest areas and sites suitable for reforestation or afforestation should be included (Pancel 1984; Weaver and Birdsey 1986).

Target Population and Sample Frame

The term population is used to define a set of elements from which a sample is selected and for which inference should be drawn. An element is defined as the basic unit that comprises the population. For example, a population can be defined as the entirety of all trees within a given forest area. Each element (here: an individual tree) can be characterized by one or several attributes (e.g., tree species, diameters, or tree height).

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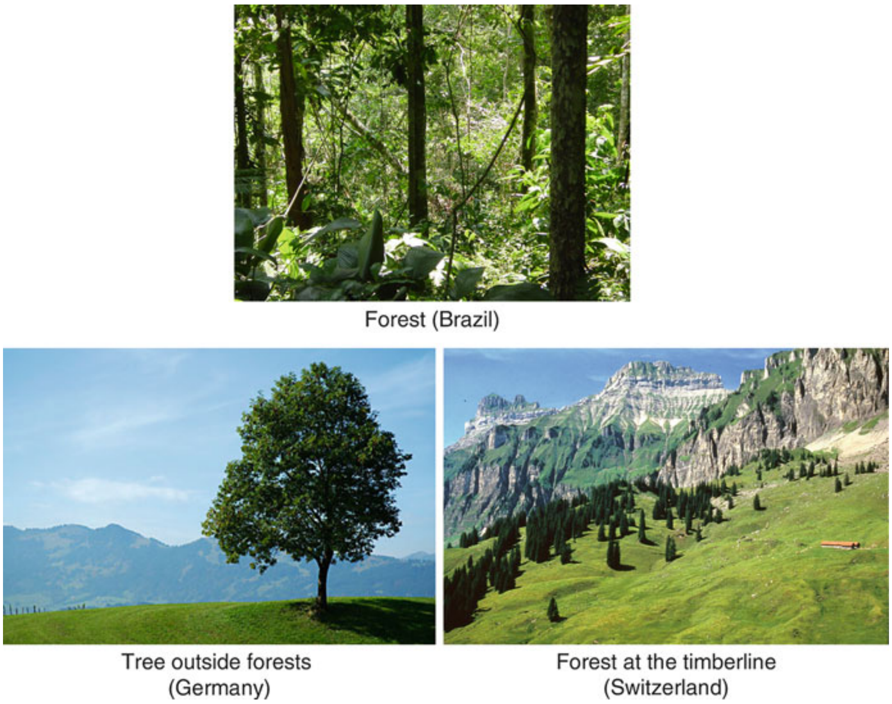

Fig. 5 Forest or non-forest?

In addition to the general term population, the more specific terms target population and sample population are used (Rossi et al. 1983). A sample population is a clearly defined population from which the sample will be selected; a target (or inferential) population is a clearly defined population to which the results will be applied. Ideally, sample and target populations coincide. However, many practical applications involve the risk that the target and the sample population differ. There are many examples of this:

- Field assessments are carried out in the vicinity of roadways or rivers in order to reduce walking time; consequently the interior parts of forests are missed.
- Locations in remote areas and thus subject to laborious and time-consuming access are less frequently visited.
- Non-accessible areas are not excluded from the target population.
- Permanent sample plots are omitted in clear-cut activities and lead to wrong information on fellings.

A sample frame (synonyms: sampling frame or survey frame) is the actual set of units from which a sample is drawn. Ideally, it coincides with the target population. Sometimes the appropriate unit is obvious, e.g., the trees in a forest stand or the logs delivered to a sawmill. However, in forest inventories, the definition of the sample frame is generally more complex. Due to the extensive areas covered, it is impossible to generate a list including all trees growing in the inventory area. This problem is resolved by defining a sample frame that includes identifying information about characteristics of the individuals. In forest inventories, it is good practice to define a sampling

[1] http://www.hyperdictionary.com/dictionary/forest

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Table 4 Forest area definitions

UNESCO	Closed forest: tree 5 m or taller with crowns interlocking
	Woodland: trees 5 m or taller with crowns not usually touching but with more than 40 % canopy cover
FAO Forest Resources Assessment 1990 (FAO 1995)	Forest (developing countries): 10 % crown cover for trees and/or bamboos
	Forest (developed countries): tree crown cover (stand density of more than 20 % of the area
FAO Forest Resources Assessment 2010 (FAO 2001)	Land with tree crown cover (or equivalent stocking level) of more than 10 % and area of more than 0.5 ha. The trees should be able to reach a minimum height of 5 m at maturity in situ. May consist either of closed forest formations where trees of various stories and undergrowth cover a high proportion of the ground or of open forest formations with a continuous vegetation cover in which tree crown cover exceeds 10 %. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10 % or tree height of 5 m are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest
	Includes: forest nurseries and seed orchards that constitute an integral part of the forest; forest roads, cleared tracts, firebreaks, and other small open areas within the forest; forest in national parks, nature reserves, and other protected areas such as those of special environmental, scientific, historical, cultural, or spiritual interest; windbreaks and shelterbelts of trees with an area of more than 0.5 ha and a width of more than 20 m. Rubberwood plantations and cork oak stands are included
	Excludes: land predominantly used for agricultural practices

frame not by reference to individual trees but by defining what is considered as a forest by a unique forest area definition (see section "Forest Area Definitions").

Quality Assurance and Quality Control

In addition to a sound design, quality assurance (QA) and quality control (QC) are essential for delivering quality information and services. According to the American Society for Quality (ASQ), QA is

> *The planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled.*

QA is any systematic process of checking to see whether a product or service being developed is meeting specified requirements. A QA system is aiming at increasing end users' confidence and the inventory's credibility and improving work processes and efficiency. A major advantage of QA systems is to catch deficiencies of the entire inventory process before they get into the final reporting.

The inventory management team decides quality assurance policies and objectives. Next, policies and requirements and how the staff can implement the quality assurance system are formally written down. Once this guideline is in place and the quality assurance procedures are implemented, the documentation of the quality of field data and data quality evaluation is ensured for operational applications (Ferretti et al. 1999; Kaufmann and Schwyzer 2001; Kitahara et al. 2009). High-quality standards and their verification lead to complete, unbiased, and factual representation of forest resources (USDA Forest Service 2012b).

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The terms quality assurance (QA) and quality control (QC) are sometimes confused. QA is an overall management plan or system, which includes the organization, planning, data collection, quality control, documentation, evaluation, and reporting activities. QA provides the information needed to ascertain that data meet defined quality standards.

Quality control (QC) refers to routine technical activities, which are used for error control. Since errors occur in the field, in remote sensing analysis, in the laboratory, in data analysis, and in the office, QC measures must be part of any of these tasks. QA and QC should result in a quality assurance project plan (QAPP), which is a written record of the entire QA/QC program.

QA Components

QA is planned and systematic activities implemented in a quality system so that quality requirements for a producing the final report will be fulfilled. It is a continual program that aims at continually improving the quality of data. The information obtained is necessary for interpreting and evaluating survey results, develop realistic objectives for measuring data quality, revising methodology to reduce efforts, improve the effectiveness of training sessions, and revising the remeasurement program for QC data (USDA Forest Service 2012).

A QA plan identifies all operations and procedures that require control. In forest inventories, that comprises all planning, development, and implementation phases (see section "Inventory Planning Phases") and thus relates to a wide range of activities, including staff recruitment and training, software development, remote sensing imagery analysis, and field assessments. For each operations and procedures, appropriate control protocols need to be defined, documented, and implemented. QA has three components: prevention, assessment and appraisal, and correction.

Prevention aims at processes that ensure that a process results in an output with desired quality before the process begins. For field assessments, prevention activities include the development of standardized definitions and procedures, which are documented in a field guide, and the agreement on data tolerance limits as well as training and calibration methods. Tolerance limits or minimum quality objectives (MQOs) define the precision of any attribute assessed in the field. For attributes on metric scales, they give the range in which measurement errors can be accepted (e.g., dbh $\pm$ 1 cm). They are more complex for attributes on nominal or ordinal scales.

Calibration generally refers to measurement instruments but can be extended to any measure taken to ensure the reproducible assessment of data. A comprehensive field manual is the base for high data quality. It lays down all definitions and measurement rules as well as procedure for assessments. FAO (2004) and USDA Forest Service (2012a) provide good examples for field manuals.

In addition, it is good practice to implement cross-checking routines and plausibility checks in mobile data loggers. For example, when for a tree with a diameter of 60 cm a tree height of 10 m is entered, a warning should be flagged. The check of data entries on the fly guarantees for the completeness of data, enables immediate corrections and verification on the plot, and thus improves data quality.

A major component of prevention activities is ***training***, which ensures that field crews have the required skills to meet the minimum quality objectives for data assessment. Training is carried out in several steps: field crews are introduced to the assessment processes and methodology, then they practice the methodology, and finally the crew performance is evaluated and documented. It is good practice to introduce a certificate at the end of a training course that approves the qualification of staff. Only certified staff members should be tasked with field assessments (Fig. 6).

Assessment and appraisal relates to the measure of data quality, which is described by accuracy, precision, completeness, comparability, detection limit, and measurement range.

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Precision is the degree of agreement among repeated measurements of the same characteristic on the same object. It shows how close measurements are to each other and how consistent and reproducible methods are. It does not mean that the results actually reflect the "true" value but rather that the assessment method provides consistent results under similar conditions. When only two replicate measurements are available, precision can be determined by the relative percent difference RPD:

$$RPD = \frac{x_1 - x_2}{(x_1 + x_2)/2} * 100$$

where x_1 is the larger and x_2 is the smaller of two measurements. Where many replicate measurements are available, the relative standard deviation RSD is a useable measure to quantify precision:

$$RSD = \frac{s}{\bar{x}} * 100$$

where s is the standard deviation and x is the mean of the replicate measurements. The smaller RSD and RPD are, the more precise are the measurements.

Accuracy refers to the size of deviations from the true value. The smaller the difference between a measured and a "true" value, the more accurate is the measurement. Measurement accuracy can be determined by comparing a standard reference material to measurements of this material. This process will help to identify if measurement techniques or measures of individual observers are biased. Where data on nominal or ordinal scales are assessed (e.g., tree species), RSD and RPD cannot be calculated. Here the percentage of correctly classified observations is a good measure for data quality.

Completeness describes a measure of the number of samples or measurements that need to be taken. Field crews can either not collect as many data as planned on a field plot or exclude entire plots. The percent completeness %C is a measure on how much of the desired data is assessed in the field:

$$\%\mathrm{C} = \left(\frac{\mathrm{v}}{\mathrm{T}}\right) * 100$$

where v is the number of measurements taken and T is the total number of desired measurements.

Comparability describes the extent to which data can be compared directly to either data from previous assessments or data from other studies. It is a useful measure for ensuring data quality in inventories at successive occasions.

Detection limit and measurement range applies to the reliability of measuring instruments. Measurement range specifies the range of reliable measurements. Detection limit is defined as the lowest resolution the methods and equipment can detect and report to be greater than zero. Readings below the detection limit are too unreliable to use. As readings approach the detection limit, they become less and less reliable. Manufactures of instruments generally provide information on detection limits and measurement ranges.

Correction aims at the improvement of measurement and assessment procedures. The information from assessment and appraisal is used to identify individual procedures that result in data that do not comply with the desired quality and need improvement. In pilot surveys that are conducted under given guidelines in order to verify the suitability of assessment methods, corrections are an

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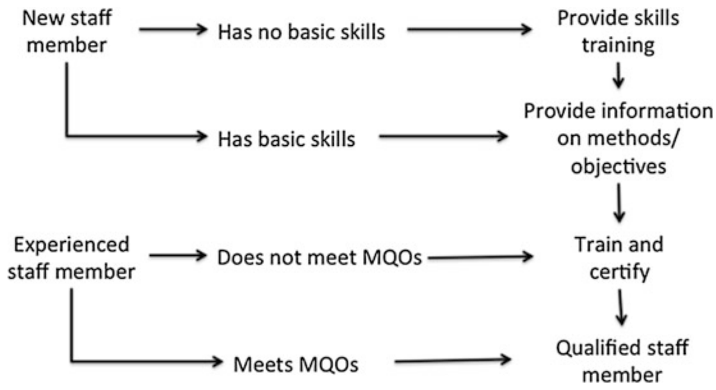

Fig. 6 Structure of training (After USDA Forest Service 2012)

important step to improve data quality. In exceptional cases, corrections can be applied during regular field assessments. However, in these situations, the comparability of data before and after corrections needs to be carefully studied.

QC Components

QC is the observation techniques and activities used to fulfill requirements for quality. In forest inventories, they are routine procedures to control the data collection process. Inspections carried out during the entire data collection phase are a vital part of QC. It is good practice to identify an experienced field crew as QA inspection crew, who are responsible for the inspection and training of production crews, are involved in the routine data assessment. According to USDA Forest Service (2012), there are different types of inspections:

Hot checks are inspections during training courses. The QC inspection crew visits a plot together with a production crew. Immediate feedback on data quality is provided, and data errors are corrected. Hot checks can either take place on training plots, which are established for training only, or on ordinary field plots.

Exit checks are used for training and for the evaluation of the readiness of a production crew for certification (see Fig. 6). The QC inspection crew has the complete set of data available and visits the plot together with the production crew. Data errors are discussed and corrected.

Cold checks are performed on production plots only and are part of the training or the regular QC program. Any production plot recently visited by field crews can be selected for cold checks. The production crews do not know, which plot will be selected, so that they cannot adjust their performance as a result of that knowledge. Cold checks are single-blind measurements, as the QC inspection crews has the completed data sets assessed by the production crew at hand. The inspection can relate to the whole or only to parts of the regular measurements on plots. Data errors are corrected. It is good practice to conduct cold checks within a couple of weeks after training with high intensity in order to verify if production crews meet the quality standards under field conditions. The QC inspection crew remeasures the plots and before leaving the plot compares the measurements with the data recorded by production crews. The results are documented and discussed with the field crews on short notice. Field crews who fail to meet the quality standards are identified and subject to additional training. Field crews failing to meet the quality standards repeatedly may be removed from the program. Where data quality is poor, plots may be rejected and remeasured.

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Blind checks are a reassessment of plots by QC field crews or by an alternative field crew without knowing the data of the previous assessment. Field crews do not know which plots will be selected for blind checks. Plots for blind checks are randomly selected after production plot data have been submitted. It is good practice to select up to 10 % of the production plots for blind checks (Kaufmann and Schwyzer 2001; Kitahara et al. 2009, USDA Forest Service 2012).

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